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Abandoned, lost and discarded fishing gear 'ghost nets' are increasing through time in Northern Australia

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ABSTRACT

The remote Gulf of Carpentaria (GoC) represents 10% of Australia's coastline. This large, shallow sea supports high-value fishing activities and habitat for threatened species, and is a sink for abandoned, lost and discarded fishing gear (ALDFG) 'ghost nets', most originating from fishing activities outside of Australia's Exclusive Economic Zone. With growing concerns about the plastic waste along the world's coastlines, we retrospectively analyzed ghost net sighting information from four aerial surveys across 15 years, to investigate whether densities of ghost nets are changing through time or in space. We found an increase in ghost nets, despite more than a decade of illegal fishing countermeasure and clean-up efforts in the broader region. This demonstrates that the input of ALDFG into the system currently overwhelms the substantial net removal activities. We make recommendations for improving monitoring and consider the underlying drivers of nets being lost to improve ghost gear management on land and at sea.

1. Introduction

There is growing concern about the increasing quantities of plastic waste, including lost fishing gear, washing ashore across the world's coastline (Stelfox et al., 2016; Vegter et al., 2014). In remote coastal areas, plastic waste is causing environmental harm to otherwise pristine coastal environs relatively free from human disturbance. With both legal and illegal fishing activities, fishing gear can be abandoned, lost or otherwise discarded. Such gear is called 'Abandoned, Lost or Discarded Fishing Gear' (ALDFG) and is known to comprise a substantial amount of global marine plastic pollution (Derraik, 2002; Richardson et al., 2018). In recent years, attention has increasingly focused on Illegal, Unreported and Unregulated (IUU) fishing. Illegal fishing occurs both on the high seas and within national jurisdictional waters with detrimental consequences for food security, marine ecosystem health and the millions of people who rely on the ocean for their livelihoods, in addition to creating plastic pollution through ALDFG.

The Gulf of Carpentaria in Australia's north is considered one of the most remote coastal environments in the world and is one such remote coastal area that is at risk from increasing plastic pollution (Galaiduk et al., 2020; Kiessling, 2003; Wilcox et al., 2013). The Gulf of Carpentaria (GoC) in tropical northern Australia is a shallow inland sea, with a maximum depth of 70 m, that occurs between northern Australia, Indonesia and Papua New Guinea (Chivas et al., 2001). The GoC coastline represents approximately 10% of the length of the Australian coastline and spans two Australian states, Queensland and Western Australia (Chivas et al., 2001).

The remote coastal environments of the GoC are an important part of the concept of 'sea country' for a number of Australian Aboriginal and Torres Strait Islander traditional owner groups who maintain strong cultural connection to GoC coastal habitats. For Australian Aboriginal and Torres Strait Islander peoples, sea country represents more than a geographic area, and culturally or spiritually, includes all living things, beliefs, values, creation spirits and cultural obligations connected to that area (Rist et al., 2019). The important cultural values of the GoC coastal environment are intrinsically linked to the ecologically diverse coastal habitat of the region.

The shallow inshore waters, mangroves, saltmarsh and seagrass

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meadows (Poiner et al., 1987) within the GoC serve as nurseries to numerous fish (Blaber et al., 1995) and prawns species, which supply commercial prawn fisheries in the region (Coles and Lee Long, 1985; Somers, 1994). The Gulf is also home to numerous threatened and endangered species including dugong (Bayliss and Freeland, 1989; Groom et al., 2015), sea turtles (Hamann et al., 2006), sawfishes (Peverell, 2005) and sharks (Salini et al., 1992) which inhabit the shallow waters. The movement through the GoC of ALDFG or 'ghost nets' exacts a substantial toll on coastal and marine wildlife, ensnaring marine turtles, as well as dugong, crocodiles, sawfish, hammerhead sharks, sea snakes, and thousands of invertebrates (Gunn et al., 2010; Phillips, 2017; Wilcox et al., 2013).

Within the Gulf of Carpentaria, it is estimated that more than 85% of the ghost nets found along the coastline originate from outside of Australia's Exclusive Economic Zone (EEZ), most likely from the nearby Arafura Sea (Edyvane and Penny, 2017). With currents and monsoonal winds, nets that are lost or discarded in the Arafura sea can be transported to the neighbouring Gulf of Carpentaria, causing harm to wildlife (Gunn et al., 2010; Wilcox et al., 2013). Though ALDFG comes from a variety of origins, ghost nets that are thought to originate from Taiwan, Indonesia and Japan have been responsible for entangling the majority of marine wildlife in northern Australia (Kiessling, 2003).

Fishing gear is lost from vessels for a variety of reasons, including but not limited to stowed gear being washed overboard, gear being lost or abandoned during fishing operations and nets or net repairs being discarded while at sea (Richardson et al., 2018). The underpinning reasons for these losses include vessels operating in poor weather (storms or high seas), vessels being inadequately maintained, gear being improperly stored, fishers working in suboptimal conditions and environments (for example, working in marginal habitat due to overcrowding/overcapacity), crew being inadequately trained or being inexperienced, and gear being inadequately marked and/or maintained (Richardson et al., 2018; Richardson et al., 2019).

ALDGF originates from fishing vessels operating both legally and illegally and from numerous jurisdictions that operate in the region, including in the Arafura Sea which is located between northern Australia, Indonesia, Timor-Leste and Papua New Guinea and bordering the GoC (Kiessling, 2003). Until recently, trawl net fishing made up the majority of fishing in the region (Richardson et al., 2018). However, in 2015, Indonesia enacted the Ministerial Degree of the Ministry of Marine Affairs and Fisheries No. 2/PERMEN-KP/2015 on the Prohibition of the Usage of Trawl and Seine Nets in Indonesia Fishery Management Area. This decree banned all trawl fishing countrywide beginning in 2018, including in the Arafura Sea (Richardson et al., 2018). Consequently, a reduction ghost gear would be expected (Richardson et al., 2019).

In Indonesian waters, including the parts of the Arafura sea, IUU fishing involves both local fishers and the theft of fish from Indonesian marine territories by foreign ships (Tarigan, 2018). This poaching of marine resources represents a cost to the Indonesian economy estimated at approximately Rp 30 trillion per year (Tarigan, 2018). Due to the negative social, political and economic impact of IUU fishing on communities and legal fishing operators, Indonesian authorities have been active in the implementation a range of countermeasures to reduce illegal fishing in Indonesia (Chapsos et al., 2019; Tarigan, 2018). The introduction of IUU fishing countermeasures can benefit the environment through the reduction ALDGF 'ghost gear' at its source.

In the last decade, the social and political awareness of the 'ghost gear' issue has grown substantially, both locally and internationally. In addition to reduction of ghost gear at its source, there has been increasing attention to coastal clean-up efforts and removal of beached ghost gear. Within Australia, the Indigenous Ranger Program across northern Australia has evolved and grown. Across the northern region, Indigenous ranger groups continue to remove nets on their country, supported through the GhostNets Australia (GNA), initiated in 2004, and operating under the principle of 'saltwater people working together'. Numerous projects targeting ghost net removal have been operational since the early 2000's with support of the Australian Government (Fig. 1). Thousands of nets have been recorded and removed by local ranger groups within this remote region, yielding multiple benefits including new livelihood skills, converting ghost nets to artwork (with associated domestic and international recognition), and improved mental health and well-being (Gunn et al., 2010). Collectively, as of 2015, nearly 15,000 ghost nets had been removed from the region. The net removal program has extended beyond Ranger groups working in the Gulf of Carpentaria to include the Torres Strait, the western part of the Northern Territory coast, and parts of the Kimberly coastline in Western Australia.

In recognition of the issue, there is now a multi-stakeholder alliance of fishing industry, private sector, multinational corporations, non-government organizations, academics and governments called the Global Ghost Gear Initiative (GGGI). The GGGI is focused on solving the problem of derelict fishing gear worldwide (https://www.ghostgear.org/). In this study, we aimed to investigate changes in the number of ghost nets along the shoreline through space and time in the Gulf of Carpentaria, in northern Australia. Given the amount of effort that has gone into removing ghost nets in northern Australia and recent changes in legislation in Indonesia, we hypothesized an overall decrease in ghost nets within the region during the study period (2004–2020). We contextualize these findings in view of the continued operation of programs that remove ghost nets from the shorelines of the Gulf of Carpentaria to ultimately provide recommendations to improve ghost gear management on land and at sea.

2. Methodology

2.1. Aerial surveys

We retrospectively compiled data from coastal aerial surveys across the northern Australian region within the Gulf of Carpentaria (Fig. 2). Aerial surveys were conducted by individual spotters in a helicopter, taking place during each November 2004, December 2017, September 2019, and February 2020. The survey area represented approximately 2367 km of Australian coastline in the Gulf of Carpentaria, from Peak Point/Punsand and Horn Island (10.7240°S 142.4158°E) in Cape York, Queensland, to the Gove Peninsula (12.3128°S, 136.9861°E) in the Northern Territory (excluding 119 km of coastline in the deltas of the Embley and Mission rivers near Weipa), 218 km around Mornington and Derham Islands. The entire survey area was not covered by each aerial survey (see Table 1, Text S1).

The 2004 survey spanned the entire GoC coastline between Peak Point/Punsand and Horn Island in Cape York, Queensland, to the Gove Peninsula in the Northern Territory. The surveys conducted in 2017 and 2019 (Duke et al., 2020a; Duke et al., 2020b) began in Weipa, Queensland (12.6332°S, 141.8559°E), following the GoC coastline until Numbulwar, Western Australia (14.3058°S, 135.7353°E). The 2020 survey was the shortest of the four, spanning from Weipa to Peak Point/Punsand Queensland.

The data collected included point data with a GPS location of each net sighted along the survey route during 2004, 2017 and 2019. For the 2020 survey, data was provided in the form of the total number of nets counted along specific survey leg between defined geographic features. For the 2020 survey, we used the information provided on the number of nets per survey leg to generate randomized GPS locations along the coastline for the number of nets recorded in each survey leg (See Text S1. Extended survey methodology). Photographs of the coastline were taken during the 2017 and 2019 surveys (Duke et al., 2020a; Duke et al., 2020b).

Given that the aims of this study to identify whether ghost nets density had changed in space and time, and that some survey areas were not observed during all four of the survey periods, some locations were excluded from analyses (e.g. those areas that were only surveyed once). These locations include Wellesley Islands (surveyed in 2017 only),

Fig. 1. Photograph of ghost net on the Gulf of Carpentaria coastline, northern Australia, during aerial helicopter surveys.

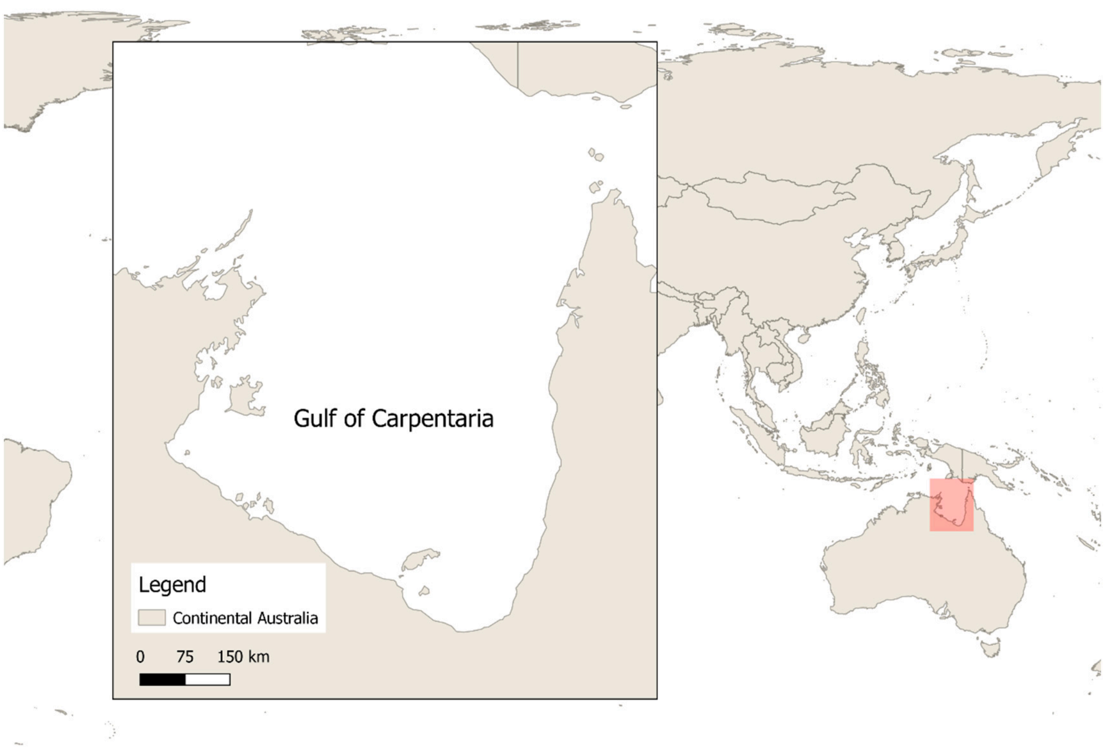

Fig. 2. Map showing the location of the Gulf of Carpentaria in northern Australia, within a global context.

regional Northern Territory north of Isle Woodah (surveyed 2004 only) and Prince of Wales Island/Horn Island and surrounding islands (surveyed 2004 only). Locations that were not surveyed were also not included in this analysis. This includes most of the islands in the Gulf of Carpentaria (except where specifically mentioned as included), including larger islands such as Groote Eylandt. Provided a similar route is flown by the helicopter, from a similar height, the data collected from aerial surveys are comparable between years. Ghost nets recorded by aerial surveys are best considered an underestimate of the true number of nets present along the coastlines, as aerial surveys are less likely to detect smaller fragments of net, nets buried under sand or those that may be obscured by or hidden in vegetation. For a detailed description of the survey routes undertaken, see Text S1. Extended survey methodology.

2.2. Analysis approach

To monitor changes in beached ghost net density across the Gulf of Carpentaria, we divided the GoC region to $1^0 \times 1^0$ grid cells, allowing us

Table 1
Survey effort (kilometers of coastline surveyed per day of aerial surveys) during 2004, 2017, 2019 and 2020 helicopter surveys.

Survey year	Date	Start	End	Nets reported	Coastline surveyed (km)	Notes
2004	17 Nov	Gove	Borroloola	125	878	Measured coastline to/from Roper Gulf rather than the inland Borroloola township.
2004	18 Nov	Borroloola	Karumba	1	593	Measured coastline to/from Roper Gulf rather than the inland Borroloola township.
2004	19 Nov	Karumba	Weipa	83	524	Excluded Embley river delta.
2004	20 Nov	Weipa	Horn island	123	372	Excluded Mission river delta.
2004	20 Nov	Horn island	Horn island	338	84	Coastline measurement Horn Island and Prince of Wales Island. Nets were on Horn Island, Prince of Wales Island, Wednesday Island, Friday Island and Goode Island.
2017	1 Dec	Weipa	Pormpurraw	120	288	
2017	2 Dec	Pormpurraw	Nassau river	8	123	
2017	4 Dec	Nassau river	Kurumba	3	197	
2017	5 Dec	Karumba	Nicholson river	3	145	
2017	6 Dec	Nicholson river	Tully inlet	7	202	
2017	7 Dec	Mornington island	Mornington island	12	218	
2017	8 Dec	Tully inlet	Borroloola	18	182	
2017	9 Dec	Borroloola	Cox river	21	209	
2017	10 Dec	Cox river	Numbulwar	17	130	
2017	11 Dec	Numbulwar	North of Woodah Island	56	232	
2019	12 Sep	Weipa	Kendall river	241	204	
2019	13 Sep	Kendall river	Nassau river	40	207	
2019	14 Sep	Nassau river	Kurumba	25	197	
2019	16 Sep	Kurumba	Nicholson river	22	145	
2019	17 Sep	Nicholson river	Robinson river	83	327	
2019	18 Sep	Robinson river	Cox river	23	231	
2019	20 Sep	Cox river	Numbulwar	140	130	
2019	21 Sep	Numbulwar	Cape Barrow	127	91	
2020	28 Feb	Weipa	MacDonald river	300	260	
2020	29 Feb	MacDonald river	Punsand/Peak Point	479	113	
2020	1 Mar	Weipa	past Aurukun	643	122	

to amalgamate the net location GPS point data collected over multiple years from each of the four helicopter surveys. Each $1^0 \times 1^0$ grid cell represents an area of approximately 111 × 111 km (sensu Wilcox et al., 2013, Fig. 3). Due to tortuosity of the coastline, the actual length of coastline within each 1^0 grid cell varies (see Table 3 for values).

We calculated coastline distances using QGIS version 3.18.0. This was a first step required to ensure geographic distances were consistent among survey years. To determine the density of beached ghost nets per grid cell, we divided the net count per grid cell by the length of coastline per grid cell.

Statistical analysis was conducted using a Generalized Additive Model (GAM) with the "mgcv" package (Wood, 2019) in R version 3.5.1 (R Core Team, 2018). This approach performs hypothesis testing and allows models to be compared to be fitted to the same data using the same smoothing parameter selection function (Wood, 2019).

2.3. Ghost net hotspots and changes through time: accounting for survey effort and predicting the density of nets

To estimate the 'actual' number of ghost nets occurring in each grid cell, we needed to adapt the net count data recorded each year to account for the survey effort in different years. Survey effort: the number of observers and time spent per survey area and data collection approaches were not entirely consistent among surveys (See Text S1. Extended survey methodology). To account for survey effort, we summarized coastline coverage data to estimate 'effort' based on the number of coastal kilometers surveyed over each helicopter day (Table 1). Ideally, the number of survey flight hours would provide more accurate survey effort, but this information was not available across all surveys. As noted previously, we used QGIS (a free and open-source Geographic Information Systems platform) and the ESRI (Environmental Systems Research Institute) "Coastlines" package to measure and quantify the length of the coastline across the Gulf of Carpentaria.

We used a modelling approach to standardise net counts, incorporating survey effort, and predict the density of nets where there was missing data. We used General Additive Models (GAM)s with a Tweedie distribution (R package "mgcv" (Wood, 2019)), selected due to the commonality of zero net counts in the data. As part of the data validation process, we also visually validated data, ensuring zero values were included into each surveyed grid cell where no nets were detected in a survey year. GAMs were used to assess the relationship between the number of nets per grid cell, the grid cell location, the length of the coastline, year of survey, survey effort (1/number of kilometers of coastline surveyed per day), the latitude of survey grid cell (1^0) and longitude of survey grid cell (1^0), examining both additive (+) and interactive (x) relationships, examining a total of seven models

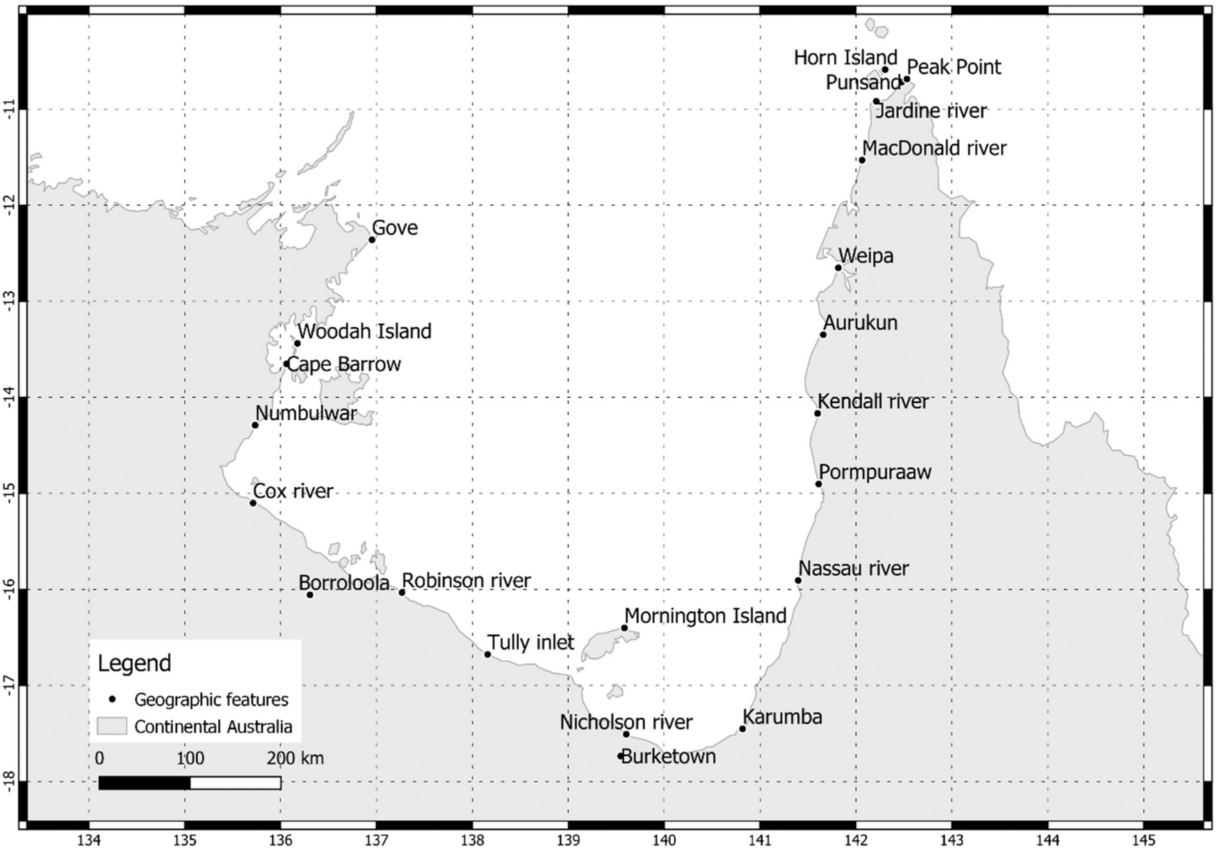

Fig. 3. Map showing a gridded map of the Gulf of Carpentaria. Each $1^0 \times 1^0$ grid cell represents an area of approximately 111 × 111 km.

Table 2
Comparison of general additive models (GAMs) that examine the relationship between number of counted nets and survey effort parameters for each 1^0 grid cell. Model 4 (bold) is the best model, based on AIC. Tested models that did not converge are not included in this table.

Model	Model parameters	AIC
0) Null model	Number of nets ~1, offset = effort.	548.8
1) Addition only model	Number of nets ~ Grid cell + Coastline length + Year +1^0 latitude * 1^0 longitude, offset = effort.	498.7
2) Interaction between year and location	Number of nets ~ Grid cell + Coastline length + Year * 1^0 latitude * 1^0 longitude, offset = effort.	486.5
3) Interaction between coastline length and year	Number of nets ~ Grid cell + Coastline length * Year +1^0 latitude * 1^0 longitude, offset = effort.	494.9
4) Interaction between coastline length, year and location	**Number of nets ~ Grid cell + Coastline length * Year * 1^0 latitude * 1^0 longitude, offset = effort.**	**484.0**
5) Interaction between coastline length and location	Number of nets ~ Grid cell + Year + Coastline length * 1^0 latitude * 1^0 longitude, offset = effort.	498.5
6) Interaction between grid cell and coastline length	Number of nets ~ Grid cell * Coastline length + Year +1^0 latitude * 1^0 longitude, offset = effort.	499.3
7) Interaction between grid cell and coastline length, year and location	Number of nets ~ Grid cell * Coastline length + Year * 1^0 latitude * 1^0 longitude, offset = effort.	486.9

(Table 2). Akaike Information Criterion (AIC) was used to choose the GAM that best fit the data and comparing these to the null model. Using AIC, the best model is that which has the lowest AIC, though models which differ by a value less than 2 may be considered equivalent (Burnham and Anderson, 2002) (see Table 2).

Using the best model (see paragraph above), we predicted the number of nets for each grid cell, for each year, in a scenario where survey effort remained consistent. We performed this prediction based on the median survey effort of 205 km of coastline surveyed per day. We report the predicted number of nets for each survey across each of the 20 grid cells surveyed. In addition, we amalgamate these grid cells in both Queensland and Western Australia, the two Australian states encompassed by the GoC coastline.

3. Results

3.1. Ghost net hotspots

Based on the four helicopter surveys and our modelling approach (model 4, which had the lowest AIC), the highest number of nets per kilometre was predicted to occur in the northern Cape York Peninsula of Queensland, including the coastline passing Vrilya point, Cotterell creek, Doughboy river, MacDonald river (QLD) (Figs. 4, 5; Table 3). Another hotspot occurs south of the Gove Peninsula. The southern portion of the Gulf of Carpentaria, near the Queensland/Northern territory border, was predicted to contain the fewest nets (Table 3).

3.2. Ghost net changes through time

The number of ghost nets in most grid cell locations (85% or 17 of 20) increased from 2004 through the 2020 surveys (Fig. 6, Table 3). However, density of beached ghost nets in three grid cells (15%) appears to be decreasing. These changes through time differed between grid cells in Queensland and the Northern Territory.

In Queensland, the number of beached ghost nets increased in all but one grid cell between 2004 and 2020 across all Queensland grid cells (Fig. 6). The sharpest increase occurred at the grid cells containing Weipa, Mapoon, Boyd point (QLD) (−13, 141) and Vrilya point,

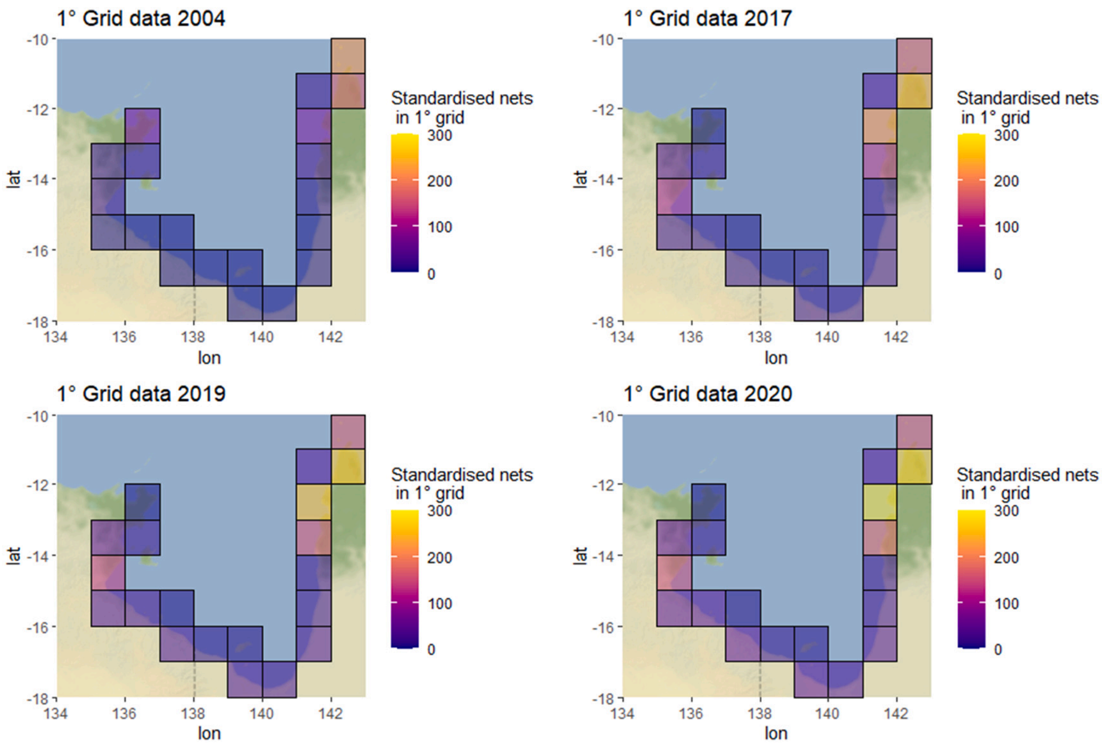

Fig. 4. Effort-standardised number of nets predicted to occur per 10 grid cell. The mapped density of nets per grid cell is not adjusted for the length of coastline per grid cell.

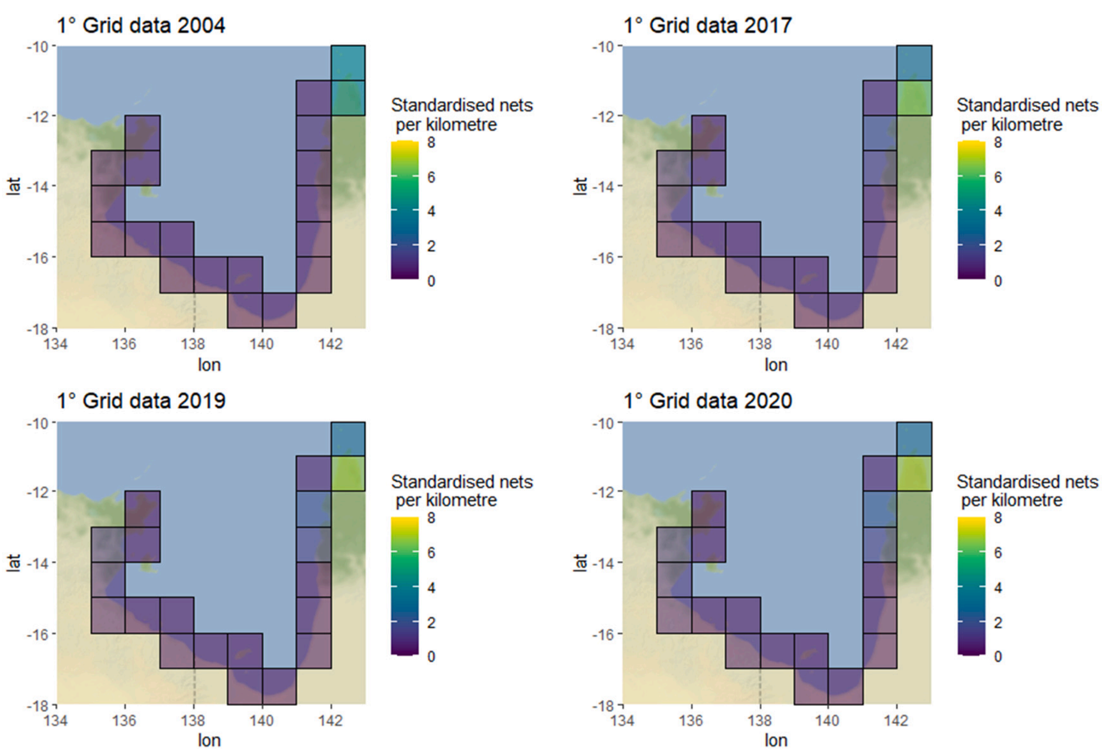

Fig. 5. The number of nets predicted to occur per kilometre of coastline in each grid cell for 2004, 2017, 2019 and 2020.

Cotterell creek, Doughboy river, MacDonald river (QLD) (−12, 142), which gained 225.5 and 114.4 nets respectively between 2004 and 2020.

The northern neighbouring grid cell (−11, 142), containing Horn island, Peak point/Punsand, Jardine river (QLD), likewise demonstrated high numbers of beached nets during 2004, standardised at 222.9 nets. However, this grid cell (−11, 142), was the only location in Queensland where the number of beached nets appeared to have decreased over time, with a reduction to 160.4 nets/km in 2020 (Table 3).

Across the Northern Territory, the change in the number of ghost

Table 3
Changes through time of standardised and predicted ghost nets per grid cell in the Gulf of Carpentaria.

Grid cell	Geographic features	2004	2017	2019	2020	Increasing or decreasing	Change
−11, 142	Horn island, Peak point/Punsand, Jardine river (QLD)	222.9	170.6	163.7	160.4	Decreasing	−62.5
−12, 141	Cullen point (QLD)	17.2	30.5	33.3	34.8	Increasing	17.6
−12, 142	Vrilya point, Cotterell creek, Doughboy river, MacDonald river (QLD)	163.5	251.6	268.8	277.9	Increasing	114.4
−13, 136	Gove (NT)	63.9	1.6	0.9	0.7	Decreasing	−63.2
−13, 141	Weipa, Mapoon, Boyd point (QLD)	66.9	219.9	264.1	289.4	Increasing	222.5
−14, 135	Cape Barrow (NT)	13.2	36.8	43.1	46.7	Increasing	33.5
−14, 136	Walker river (NT)	18.5	16	15.6	15.5	Decreasing	−3
−14, 141	Aurukun, Norman creek, southern end of 2020 survey (QLD)	25.2	119.6	151.9	171.2	Increasing	146
−15, 135	Numbulwar (NT)	17.7	95.1	123.2	140.2	Increasing	122.5
−15, 141	Kendall river, Pormpuraaw (QLD)	7.1	16.8	19.1	20.4	Increasing	13.3
−16, 135	Cox river (NT)	0.6	17.9	30	38.9	Increasing	38.3
−16, 136	Roper gulf coast and islands (NT)	0.2	13.3	25.5	35.4	Increasing	35.2
−16, 137	Coast and part of Vanderlin island (NT)	0.1	3	5.1	6.7	Increasing	6.6
−16, 141	Nassau river (QLD)	1.3	14.2	20.4	24.5	Increasing	23.2
−17, 137	Robinson river, Norther Territory side of state border (NT)	0.1	13.5	28.2	40.7	Increasing	40.6
−17, 138	Tully inlet, Queensland side of state border (QLD)	0.1	5.5	10.7	15	Increasing	14.9
−17, 139	Mornington Island, Forsyth island and coast (QLD)	1.1	6.3	8.3	9.6	Increasing	8.5
−17, 141	Staaten river, Gilbert river, Dinah island nature refuge (QLD)	1.1	16.8	25.4	31.2	Increasing	30.1
−18, 139	Nicholson river (QLD)	0.2	13.3	26.5	37.4	Increasing	37.2
−18, 140	Karumba (QLD)	0.6	13.9	22.4	28.3	Increasing	27.7

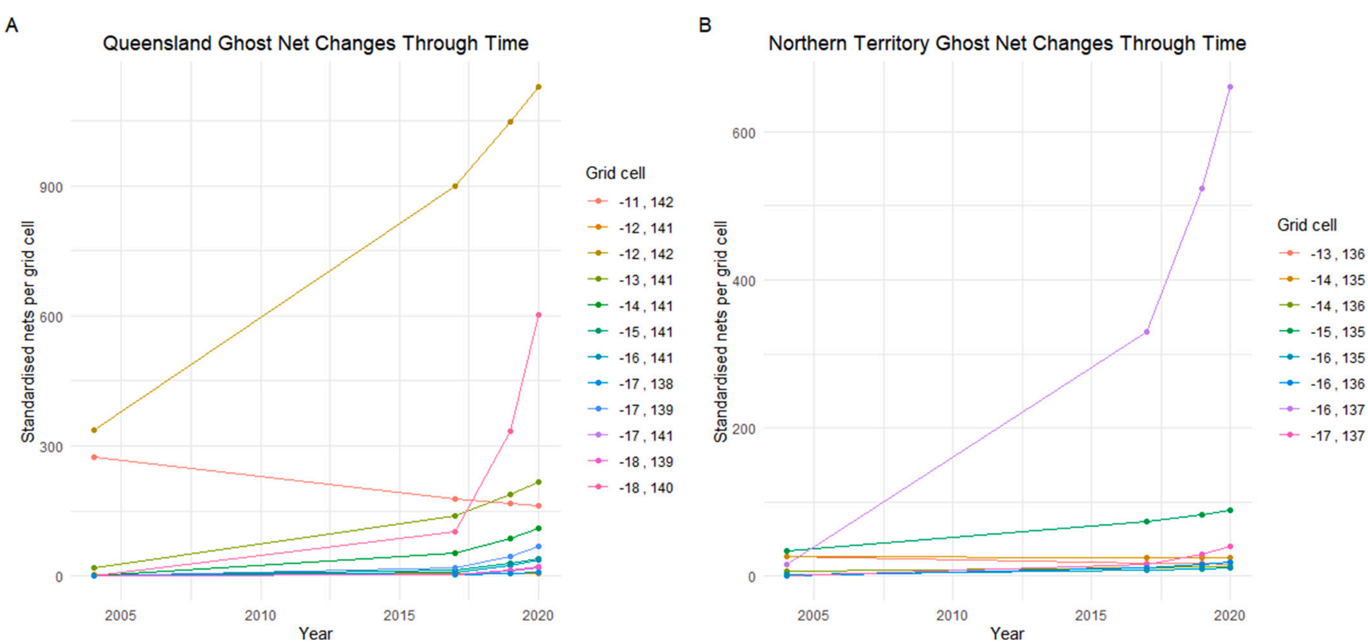

Fig. 6. Changes in net numbers through time between 2004 and 2020 in each grid cell across Queensland (Panel A) and Northern Territory (Panel B).

nets through time was not as dramatic as for Queensland (Fig. 6), except for two grid cells. The sharpest increase in predicted net density in the Northern Territory occurs on the coast and among the grid cell containing Numbulwar (−15, 135), which experienced a nine-fold increase in nets. The remaining regions within the Northern Territory showed a gradual increase (two showed a gradual decrease) in ghost nets between 2004 and 2020.

4. Discussion

Our retrospective analysis of ghost gear sightings across 15 years showed that while ghost net hotspots remain broadly consistent, net numbers in the GoC are increasing overall through time. This increase in net numbers was contrary to our hypothesis that net numbers would have decreased; this rise in nets is occurring despite the ongoing efforts to reduce the amount of ALDFG in northern Australia both at sources and at sinks of the GoC coastline. We suggest that ALDFG reduction efforts at the source are likely overwhelmed by the input of ALDFG into the system. These major reduction efforts include countermeasures to combat illegal fishing in the Arafura Sea, especially by Indonesian authorities (Tarigan, 2018) and regional beach cleaning efforts by Indigenous Ranger Programs in Australia, supported by GNA.

4.1. *Ghost net hotspots in the Gulf of Carpentaria*

Hotspots for ghost net accumulation in the Gulf of Carpentaria occur in the northern Cape York Peninsula of Queensland and inlets south of the Gove Peninsula, Northern territory. These findings reflect hotspots identified in previous studies of the same geographic region, including the 2004–2009 Summary report by GhostNets Australia, which reported that hotspots were predominantly found in the north-eastern and north-western corners of the Gulf (Heathcote et al., 2011). The Gulf of Carpentaria acts as an accumulation area or sink for ghost nets and other anthropogenic debris because of the bathymetry, geography, monsoonal seasonality and the influence of wind, waves, and currents. While previous studies have noted the high density of ghost nets in the region

(Gunn et al., 2010; Wilcox et al., 2013), it is worth noting that if the loss of fishing nets is not abated, the issue of nets and other anthropogenic debris will continue within the region. The Gulf of Carpentaria has a high biodiversity value, with six of the seven threatened marine turtle species occurring here, including substantial proportions of the remaining global populations for some species (Biddle and Limpus, 2011; Limpus and Fien, 2009). The gulf's shallow waters are extensive, with seagrass and mangrove-reliant communities. Land and sea management is difficult due to the Gulf's remoteness.

4.2. Ghost net changes through time

Ghost net accumulation in some regions within the GoC is more rapid than in others. This may be an 'actual' phenomenon or may reflect clean-up activities or changes in fishing locations. It may also reflect a change in operation of the types of fishing boats that have high rates of gear becoming derelict and generating ghost nets. Information on net types, in addition to the number of nets that are stranded, would help us to answer this question.

There have been substantial changes in fisheries management practices in recent years by neighbouring countries, including Indonesia, that have resulted in a reduction of total fishing vessels within the Arafura and surrounding seas (Richardson et al., 2018). However, while there has been a prohibition of purse seine and trawl nets, there has been a concordant increase in gill nets (Australian Fisheries Management Authority, pers. comm.). Hence, it is possible that the number of nets lost may not have changed substantially, though further investigation into the types of nets washing ashore in the Gulf of Carpentaria could prove meaningful. A study of long-line fishing operators in the region showed shifts towards increased fishing effort in the Arafura Sea between 2012 and 2019 (Utama et al., 2021). Perhaps net fisheries have experienced a similar shift over time with associated losses of fishing gear in the Arafura Sea. Overall, we were surprised that given the many years of on-ground clean-up activities in which ghost nets have been removed within the Gulf of Carpentaria, an overall increase in the number of nets was detected from 2004 through 2020 from aerial surveys.

In Queensland, an increase in ghost nets in the Cape York Peninsula area has occurred despite clean-up efforts there, as noted during the 2020 northern Queensland survey. This suggests that despite on ground efforts, beached ghost nets appear to be increasing in this area. Detailed information about on-ground, local clean-up efforts would be useful to contextualize this pattern that we observed. The reason for this increase in nets is not known, though it may be due to local clean-up efforts, an artefact of the surveys that were conducted (for example, this grid cell contains several islands, and we only have information on which islands were included in the survey during 2004). Alternatively, it could be associated with greater detectability due to mangrove dieback. It is also possible that this predicted decrease is an artefact of the survey or analysis methods, as this northern point was surveyed in only two years (2004 and 2020), meaning that the data is less robust than other regions. We urge caution against overinterpretation of this finding.

One interesting observation is the sharp increase in nets at the southern Queensland latitudes. The 2004 surveys revealed very few nets in these regions, but later (2017, 2019) surveys showed nets accumulating in this area. From these data alone, and without more specific information on clean-up efforts here, we do not know whether all southern regions are rapidly accumulating ghost nets or whether the pattern observe reflects less clean up occurring than other sections of the Queensland coastline, given its sparse population.

Changes through time in the Northern Territory were less stark than those observed in Queensland. The sharpest decrease occurred in the grid cell containing the Gove peninsula (−13, 136), however this grid cell was only surveyed once in 2004 and therefore the expected decrease is based on modelled variables rather than actual observations of a decrease from repeated surveys, so again we urge caution in over-interpretation. Other sites within the Northern Territory were fairly consistent in the numbers of nets observed across the 16 years of aerial surveys (Fig. 6).

4.3. Caveats

The hotspots shown are influenced by a number of factors. Ghost net accumulation hotspots are likely influenced by clean-up efforts at other sites, which may be masking accumulation in other parts of the Gulf. This relates to the accessibility, geography and engagement of local Indigenous ranger groups and their activities, resources, seasonality, and other important points to consider that may affect where and how many ghost nets are observed from aerial surveys.

As only four surveys were conducted over 15+ years, more surveys with better metadata would potentially improve the confidence in results and enable a better nuanced understanding of ghost net hotspots and changes in net numbers through time. The addition of on-ground coastal net clean-up data (including location, effort, seasonality, and net types) to this aerial survey information would be useful. Hotspots reflect the arrival of ghost-nets on the beach, minus the offshore transport of ghost nets away from the site. For the moment, the findings in this report do not include clean-up efforts that may have (likely have) influenced the numbers of nets observed at particular locations. Therefore, the hotspots denoted herein may not necessarily reflect solely where the most nets are accumulating. They may also reflect the remoteness, accessibility and on-ground activities taking place within the region. Likewise, those areas where nets are not observed may reflect the intensity of on-ground clean-up efforts, rather than a region that does not or has not accumulated ghost nets or an area with insufficient forcing (wind or current) to transport nets.

In addition, it has been noted that mangrove dieback has been a very strong phenomenon across the Gulf of Carpentaria (Duke et al., 2020a; Duke et al., 2020b; Duke et al., 2021; Duke et al., 2017). Ghost nets can become snagged in mangroves; hence, it may be that the increase in ghost nets recorded across the GoC reflects the increase in detectability of nets during aerial surveys, due to lack of vegetation cover following mangrove dieback.

4.4. Gulf of Carpentaria ghost gear management in a global context

Given that an estimated nearly 6% of all fishing nets, 9% of all traps and 29% of all lines are lost around the world each year (Richardson et al., 2019), reducing fishing gear losses is critically important for economic, environmental and social reasons. To reduce gear losses at sea, there are multiple approaches that can be taken. These may include ensuring constraints on the number of fishing licenses or reducing fishing licenses that are granted and/or increasing education, inspection and enforcement (which would reduce overcrowding/overcapacity issues that result in fishing in marginal habitats) (Macfadyen et al., 2009; Richardson et al., 2018). It could also include the implementation and support of port waste facilities and buyback programs which have been shown to reduce fishers throwing old nets (or fragments of nets) overboard and increase gear recovery rates (Cho, 2009; Richardson et al., 2018; Wilcox et al., 2013). Furthermore, gear loss is associated with increased fishing effort in Arafura-Timor Sea region (sensu Richardson et al., 2018).

4.5. Recommendations for improving ghost gear management

As previously noted, the Gulf of Carpentaria is a remote region with high biodiversity value. It is home to nesting grounds for several species of vulnerable sea turtles as well as dugong, sawfish and other coastal and marine taxa. Hence, opportunities to interdict ghost nets *before* they enter the Gulf would likely reduce impacts on biodiversity and result in less damage to sensitive coastal ecosystems within the region. It appears that most nets likely enter the Gulf of Carpentaria from the northwest and move along the north-eastern shore in a clockwise direction, based on oceanographic modelling and trackers placed on nets in the region (see Wilcox et al., 2013, 2014 for detail).

Hence, we suggest the following for interdicting derelict nets at sea. First, we recommend monitoring the coastline for nets via aerial surveys (such as periodic flyovers by Maritime Border Command during regular operations). The use of satellites or drones to ascertain speed and area of movement would also be beneficial. Second, we suggest focusing aerial survey/monitoring efforts on a reasonably small area in the northeast of the Gulf with a high probability of opportunity for interdicting nets. Finally, we recommend attaching transmitters or transponders to floating nets. This can better support safer, more cost-effective net interdiction activities including net retrieval closer to shore, before entering the Gulf – such as near the port town of Weipa. These approaches could provide further opportunity of engagement with local fishers (who could be provided with devices to attach if/as they came across derelict nets) and increase local awareness of the consequences of gear loss, while supporting best fishing practices. Without both domestic and international actions to reduce the loss of nets at sea and local action to remove nets that have accumulated on beaches, ghost nets abundance will continue to increase and impact upon threatened species in the Gulf of Carpentaria and in the global ocean.

CRediT authorship contribution statement

BDH and CW conceived of this work. BDH and LR compiled the information. LR analyzed the data with support from CW. BDH and LR drafted the initial manuscript, with edits and input from CW, ND, and JM. ND and JM conducted aerial surveys and provided data for this paper.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary information

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